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Accuracy Improvement of Rotational Speed Sensors by Novel Signal Processing Method

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Abstract. A novel signal processing method is proposed for determining the rotational speed more accurately. In this method, the periodic output signal of a rotational speed sensor is filtered and then sampled in a defined time window. The sampled discrete signal is further filtered to improve its Signal-to-Noise Ratio (SNR). The rotational speed is derived by a precise determination of the signal frequency of the periodic signal under using Discrete Fourier Series (DFS) and iterative Self-Correction and optimization algorithms. From the experimental results, an accuracy of about 0.2% can be achieved. This method can be used in all kinds of rotational speed sensors and encoders with analogue signal output.

1. Introduction

Rotational speed measurement is an important operation in automation and automotive industry etc. Especially in electrical drive systems, rotational speed and position sensors are essential for a proper functionality of the whole machine [1]. With the industrial digitalization, those sensors with digital outputs are preferred for electrical drive and control systems.

There are various kinds of digital rotational speed and position sensors on market, e.g. magnetic gear tooth sensors, inductive sensors, optical grating sensors and encoders etc. Depending on their physical principles and structures, they are suitable for different applications. For example. Hall-Effect and inductive gear tooth sensors are widely used in automotive and wind turbines thanks to their robust and resistant towards harsh environments and vibrations, and wide temperature range etc. However, their resolution and accuracy are limited due to mechanical structures and physical capabilities. A Hall-Effect gear tooth sensor coupled with a 12 teeth gear can only provide 12 position impulses with a resolution of 30° if an impulse counting method is used for determining the rotational speed. In this way the relative deviation is about ±8.33% (= ±1/12, see equation (3)) if the rotational speed is 60 RPM due to the quantization errors.

Rotational speed and position sensors with high resolution and accuracy are available, e.g. optic encoders with 24 bits resolution. Nevertheless, they are comparatively very expensive, and cannot be used in harsh environments or at extreme temperature. Consequently, there is a need for low-cost, robust and reliable rotational speed and position sensors with good performance in resolution and accuracy.

In this paper, a novel signal processing method is proposed for directly determining the rotational speed and position under using sampling data from conventional rotational speed sensors. By using this method, the accuracy and resolution of the rotational speed and position measuring system can be improved noticeably. Hence, this method can be considered as a cost-effective method for improving the performances of most rotational speed sensors.

2. Conventional Digital Rotational Speed Sensors

Conventional digital rotational speed and position sensors can be modelled as shown in Figure 1. This model consists of a mechanical part (e.g. motor) and the digital sensor system. Rotational position φ and rotational speed ω are the measurerands of a rotating motor. By mechanical, magnetic or optical coupling of the motor with the sensor, a physical measurand $f_p(t)$, which is dependent of φ and ω, is obtained, so that an analog transducer like a Hall-IC or a photodiode can measure the physical variation and give out an analog signal $x(t)$, which is periodic due to the rotation. The Analog-to-Digital Converter (ADC) transforms the analog signal $x(t)$ to a discrete signal $x(k)$, which is suitable for the digital signal processing in order to calculate angle position φ_m and rotational speed ω_m.

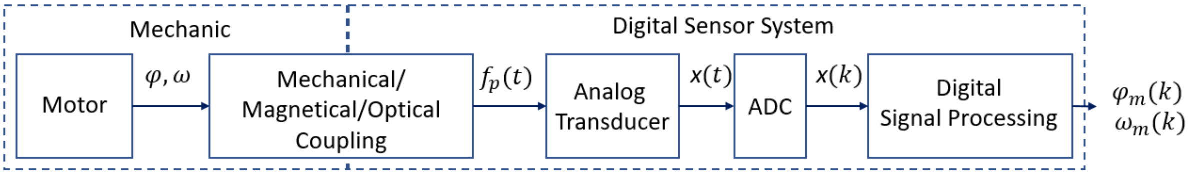

Figure 1. Structure of a conventional Digital Rotational Speed Sensor.

From this structure, it can be obtained that digital signal processing has to be considered and newly developed in order to obtain higher accuracy and resolution in position and speed.

3. Novel Signal Processing Method

Based on the objective for a new digital signal processing method and the compatibility to existing sensors like the Hall-Effect gear tooth sensor, the following solution has been proposed. Figure 2 shows the overview scheme by applying analog and digital signal processing methods on the analog periodic output signal of a rotational speed and position sensor.

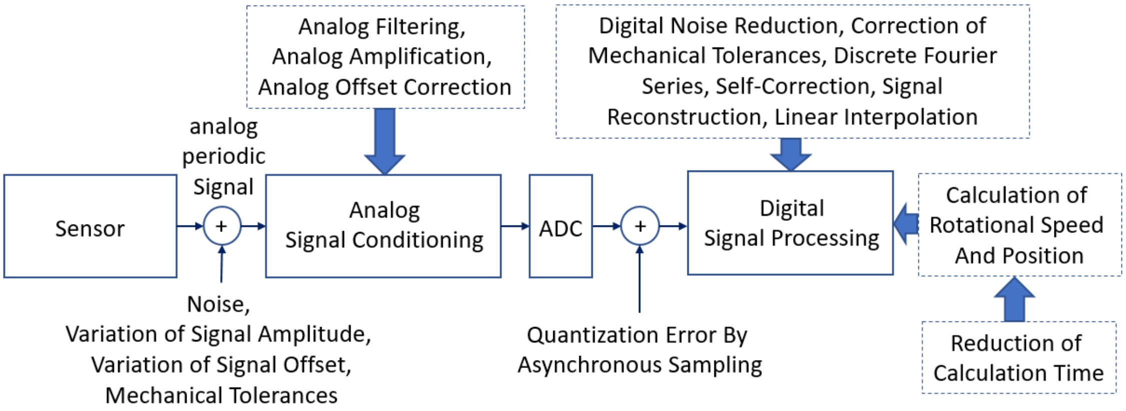

Figure 2. Overview of the solution by using analog and digital signal processing methods for more accurate determination of rotational speed and position based on a conventional speed and position sensor.

With an analog signal conditioning, distortions in the analog signal can be reduced, for example by analog low-pass filtering, signal amplitude adjustment and offset correction. Analog filtering helps to suppress noises in higher frequency range, while digital noise reduction can improve the Signal-to-Noise Ratio (SNR) in the whole frequency range. Thus, the filtered analog signal should be sampled by an ADC in a defined time window.

Digital noise reduction methods can be applied to the processing of the sampled discrete signal. Good results have been achieved with a moving average filter, which is fast and easy to implement. The best results are achieved with a Frequency-Selective Adaptive Filtering (see [2]). Table 1 lists the Signal-to-Noise Ratios (SNR) before and after the application of Frequency-Selective Adaptive Filtering on real measured sine wave signals at different rotational speeds. From the results, the SNRs are improved noticeably, so that the processed discrete signal is much better for calculating rotational speed and position.

Concerning the determination of rotational speed and position, the quantization error from the asynchronous sampling must be taken into account. If the analog signal is synchronous sampled to the digital domain, the signal frequency f_0 can be easily calculated from division of the sampling frequency f_s by an integer N_0, i.e. $f_0 = f_s/N_0$, where N_0 is the number of counted impulses during a signal period.

Table 1. SNR before and after Frequency-Selective Adaptive Filtering on real measured sine wave signals at different rotational speeds.

Rotational Speed	SNR before Filtering	SNR after Filtering
10 RPM	36.30 dB	291.9 dB
500 RPM	38.21 dB	90.31 dB
1000 RPM	38.57 dB	71.21 dB
2000 RPM	38.34 dB	69.89 dB

But practically, due to the fact, that the sampling frequency is constant and the signal frequency of the sensor output varies with the rotational speed, the relationship between both frequencies is generally summarized in the following equation:

$$f_0 = \frac{f_s}{N_0 + \alpha} \tag{1}$$

Here, an asynchronous factor α is added, so that the synchronous case only appears when $\alpha = 0$. Nevertheless, this case is more an exception, so that the precise determination of the asynchronous factor α is important for accurate rotational speed.

The proposed novel signal processing method utilizes a two-step process for achieving this goal. The first step is a coarse signal period determination. It results in N_0 as the number of samples in one signal period by applying a software Schmitt-Trigger or zero-crossing detection.

The second step is concentrated on a fine frequency determination and starts with the Discrete Fourier Series (DFS) in order to calculate the coefficients C_1 (signal amplitude), Φ_1 (phase offset) and a_0 (signal offset) from the fundamental part of the sampled periodic sensor signal in a time window of at least one full signal period. By applying an iterative Self-Correction Algorithm described in [3], these coefficients can be calculated more precisely, especially in case of asynchronous sampling.

With precise signal coefficients and N_0, the discrete sine wave signal $x(k)$, $k = 0, 1, \dots, N_0 - 1$ can be reconstructed according to the following equation

$$x(k) = \frac{a_0}{2} + C_1 \cdot \sin(2\pi \frac{k}{N_0 + \alpha} + \Phi_1) \tag{2}$$

In this equation, only the factor α is still missing, so it can be set as a variable for the optimization of the reconstructed signal with the original sampled and noise reduced signal. Depending on the effectiveness of the chosen optimization algorithm, α can be specified very precisely, so that it results in a very accurate signal frequency (according to equation (1)) and thus a very accurate rotational speed.

Rotational positions are obtained by DFS and iterative Self-Correction Algorithm by using the phase offset Φ_1. The resolution of the determined positions depends only on the resolution from the calculation and digital output. In combination with a FIFO method, continuous determination of rotational speed and position is realized. A FIFO stack can be described as a floating memory part for sampled values, in which at least one full signal period is held in, so that the calculation algorithm can always have access to the data.

4. Simulation and Experimental Results

Results in simulation and experiments should verify the improvements by the novel signal processing method. Simulations are done with a sinusoidal signal and additional white Gaussian noise. Table 2 shows the simulation results at different SNRs and constant input signal frequency under using the novel signal processing method. The average deviations and standard deviations increase with the reduction of the Signal-to Noise Ratio (SNR), for instance, the accuracy can reach about 0.1% at SNR = 27 dB.

Table 2. Simulation Results at different SNR and constant Rotational Speed under using the Novel Signal Processing Method.

SNR	Average Deviation	Standard Deviation
50 dB	0.0114%	0.0106%
30 dB	0.0574%	0.0528%
27 dB	0.0872%	0.1022%
20 dB	0.2131%	0.1688%
15 dB	0.4952%	0.3576%

The rotational speed measuring and calibration system described in [4] can be used for experimental verification of the novel rotational speed signal processing method under using different rotational speed sensors. A Hall-Effect gear tooth sensor with 12 teeth is tested. The output signal of this sensor is sinusoidal. Table 3 shows the maximum average and standard deviations from measurements under 4 different rotational speeds processed by the described method. The accuracy can be controlled within 0.2% comparison to the reference measuring system.

Table 3. Average Deviations under using a Hall-Effect Gear Tooth Sensor with 12 Teeth Gear and the novel Signal Processing Method at different Rotational Speeds. The deviations are compared to the theoretic relative deviation by using Impulse Counting Method.

Rotational Speed	Theoretic Deviation by Impulse Counting	Average Deviation
50 RPM	10.0%	0,13%
100 RPM	5.00%	0.03%
300 RPM	1.67%	0.12%
600 RPM	0.83%	0.16%
1000 RPM	0.50%	0.14%

The relative deviations by impulse counting method are also listed in the table, which are calculated by the following equation

$$\frac{\Delta\omega_m}{\omega_m} = \frac{1}{f_0} = \frac{60}{N \cdot \omega} \tag{3}$$

where ω is the rotational speed in RPM and N stands for the number of signal periods in one revolution ($N = 12$ for Hall Effect gear tooth sensor coupled with 12 teeth target gear). The accuracy of the impulse counting method is not good at low speed, but gets better with increasing speed. In comparison, the novel signal processing method guarantees nearly constant accuracy over the whole speed range.

5. Conclusions

From the experimental results, one can draw that the proposed novel signal processing is capable of improving the accuracy of all kinds of rotational speed sensors in a cost-effective way, independent from the sensor structures and rotational speed.

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